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AN EXPERIMENTAL STUDY OF MODEL FIRES

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We gratefully acknowledge the tireless efforts of the late Wallace L. Fons, leader of Project Fire Model, who had made detailed plans for the wind tunnel fires at the time of his death in October 1963. His devotion to his chosen field of work was an inspiration to his fellow workers.

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I. INTRODUCTION

In order to establish a quantitative model of the propagation of free-burning fires, it will be necessary (1) to identify the various physical processes which make up the mechanisms of fire spread and (2) to obtain an understanding of the processes and their interacting effects. A "mechanism" of fire spread will be defined as one or more processes whose combined effect determines one way in which a fire can spread. For some types of fires more than one mechanism, or group of processes, may be operating simultaneously.

One of the first models of fire spread is represented by the analysis given by Fons (1946). Fons resumed this work in 1959 after Project Fire Model was formed. Its general objectives were to determine the effect of the independent fuel and weather variables on the spread, behavior, and rate of energy output of free-burning fires in solid fuel. Detailed objectives are given in an earlier report by Fons et al (1960) and most of the results for fires in still air are given in a second report by Fons et al (1962). Much of the work in Project Fire Model has been based on steady-state laboratory fires spreading through wood cribs. The wood crib

is a special type of fuel bed in which important fuel variables such as moisture content, wood density, stick size, and stick spacing can be carefully controlled.

The first part of this report presents the results of further tests of fires in wood cribs. In one series of tests cribs of the same height and structure but with different areas, or horizontal cross-sections, were burned in still air to determine the effect of size of burning area on the rate of burning per unit area. A second group of tests in still air concerns the effect of stick size and spacing on rate of fire spread. A third series of tests was made with fires in the wind tunnel to determine the effect of wind speed on rate of spread, rate of heat output, flame length, and angle of flame tilt.

Although a quantitative model of fire propagation is not proposed, the second part of the report deals with mechanisms of fire spread. An experiment with a series of pool fires in a wind stream is described which illustrates an important ignition process involved in the spread of wind-driven fires.

II. THE EFFECT OF SIZE OF BURNING AREA ON THE BURNING RATE OF WOOD CRIBS

One of the main processes controlling the rate of spread of free-burning fires is the rate of burnout of ignited fuel. Behind the leading edge of a moving fire front is a strip of considerable width which may be designated as the burning zone. For a given rate of spread, this zone will be narrower and the flame higher when the fuels burn out rapidly than when they burn out slowly. Many factors influence the burning rate such as fuel particle spacing, fuel particle size, moisture content, possibly wind speed, and the dimensions or size of the burning area.

To determine effect of size of burning area on the burning rate, seven test burns were made with square cribs ranging in width from 0.2 feet to 1.28 feet. The cribs were constructed from 1/4-inch sticks of white fir (Abies concolor) and conditioned to a moisture content of 10.1 percent. Each crib had a stick spacing of 3/4 inch and a height of 3.1 inches. Each crib was placed over a wick of asbestos cloth soaked in a few milliliters of n-hexane (less than 3 percent of the crib weight). Both wick and crib were mounted in a shallow pan, slightly wider than the crib, supported by a direct reading balance. The entire crib was in flames from the moment of ignition and the weight was recorded at 15-second intervals throughout the burning period. For each fire the weight was plotted against time as shown for the 1.28-foot crib in figure 1. Experimental conditions and results are given in table 3 of the Appendix.

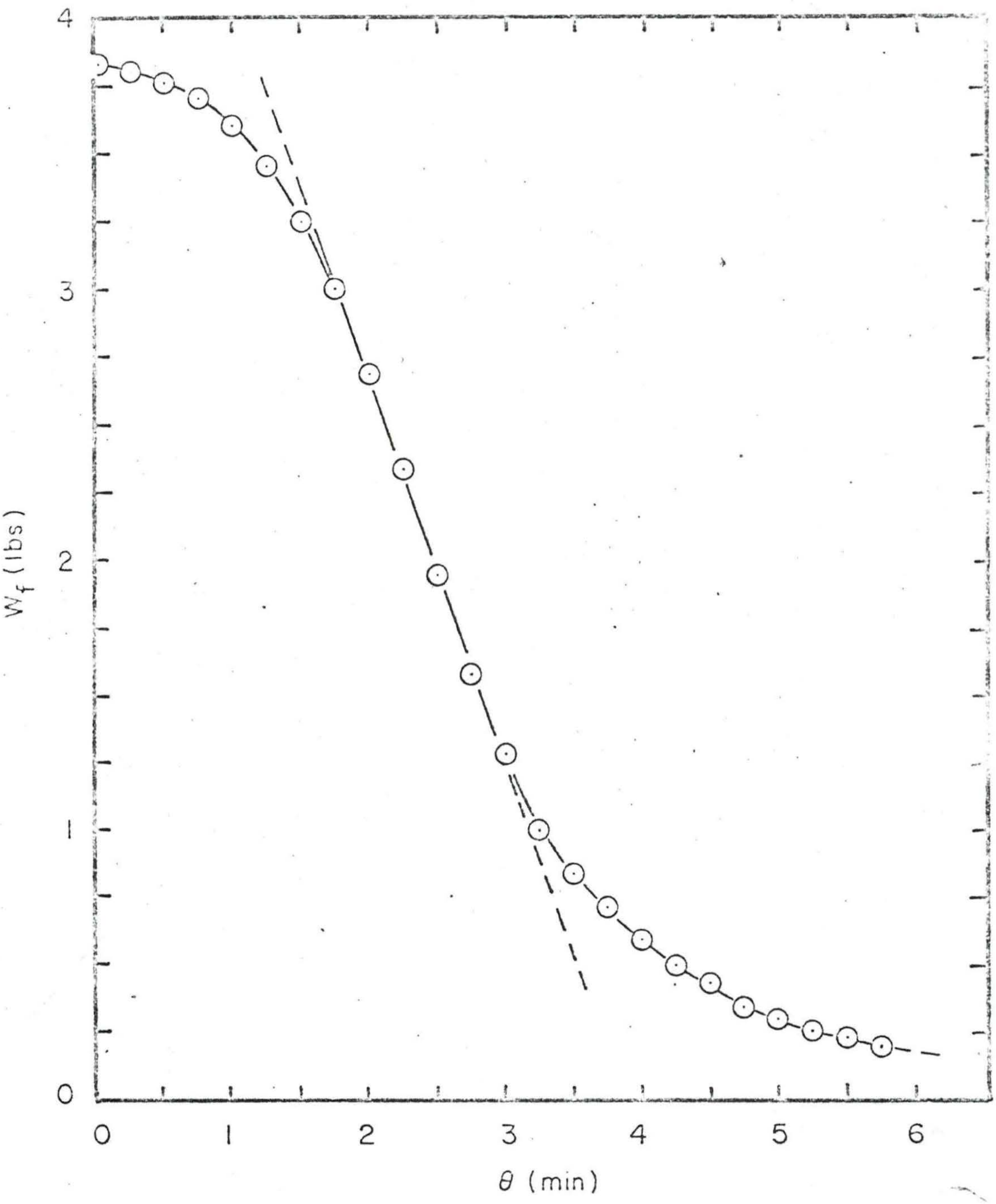

Figure 1.--The weight-time burning curve of a square wood crib with a width of 1.28 feet. The maximum burning rate was 1.58 pounds per minute.

The burning rate was given by the slope of the curve (fig. 1) which had its largest value during a period when the burning rate was nearly constant. The maximum burning rate per unit area G was calculated by the equation

$$G = \frac{1}{D^2}\left(\frac{dW_f}{d\theta}\right)_{max}$$

where G is the burning rate in $lbs/ft^2 min$, D the crib width in feet, and $(dW_f/d\theta)_{max}$ is the maximum rate of weight loss.

In figure 2, the results of the tests are shown as a mass transfer-heat transfer relationship with the dimensionless group $\frac{GD}{\nu_\infty \rho_\infty}$ plotted against the group $\frac{gD^3}{\nu_\infty^2}$ where ρ_∞ is the air density, ν_∞ the air kinematic viscosity, and g the acceleration due to gravity. This curve indicates that for the square cribs

$$\frac{GD}{\nu_\infty \rho_\infty} \propto \left(\frac{gD^3}{\nu_\infty^2}\right)^n.$$

with a value of n very close to 1/4.

Figure 3 shows that the burning rate G varies as the minus 1/4 power of the crib width D in the range of crib sizes used in these tests. From the curves in figures 2 and 3 it appears that the effect of area on the burning rate of wood cribs is similar to that for liquid fires in the region of laminar flow as reported by Spalding (1953), Rasbash et al (1956), and Fons (1961). However, as the area of liquid fires increases the burning rate reaches a minimum and then increases to approach a constant rate for the turbulent conditions over large burning pools. This behavior of liquid fuels was discussed by Hottel (1959). Whether solid fuels will

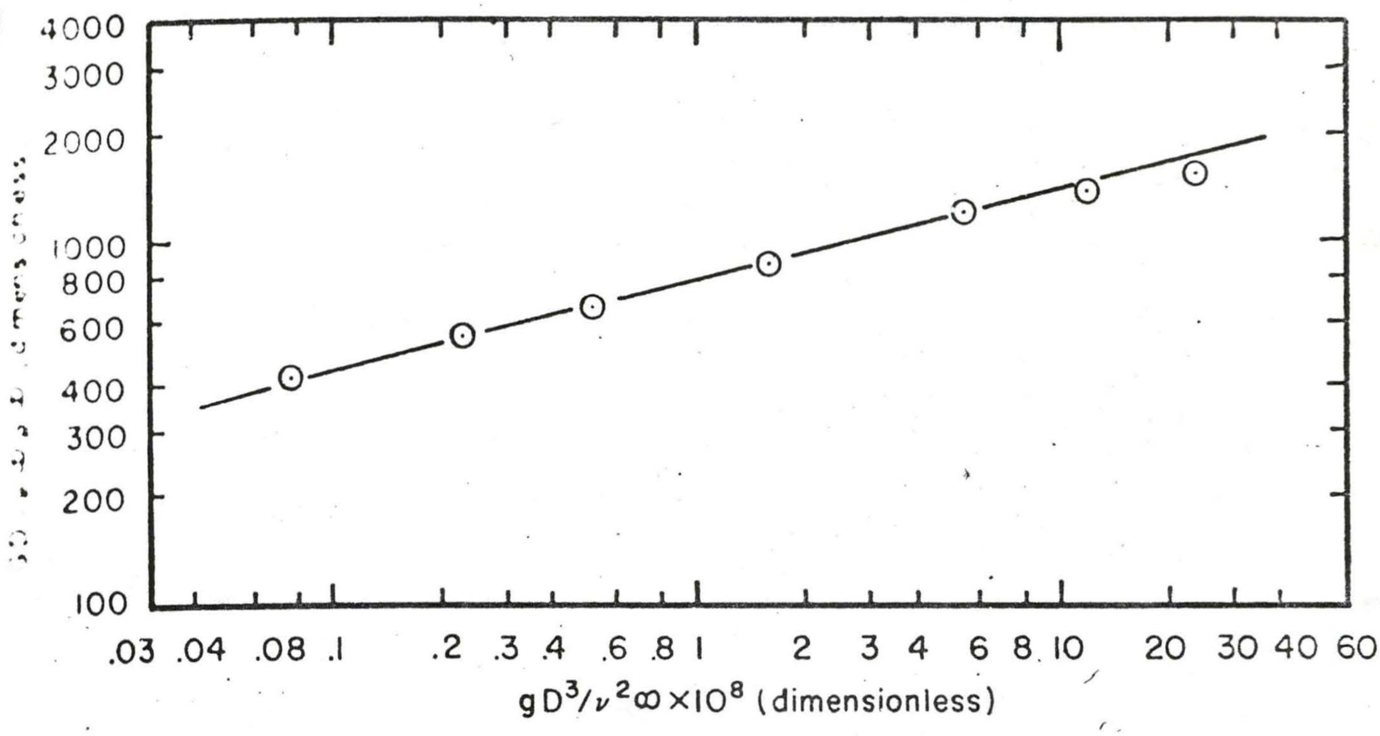

Figure 2.--The mass transfer-heat transfer correlation for a square crib burning in still air.

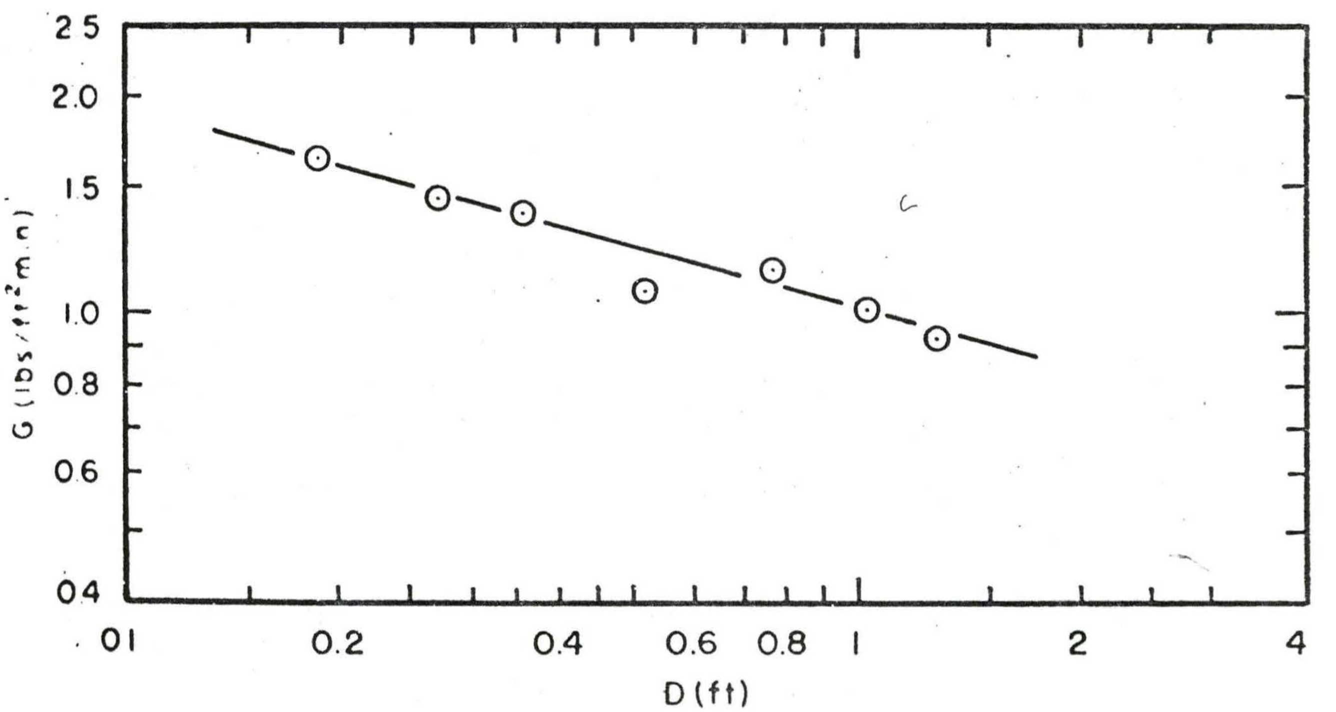

Figure 3.--Unit area burning rate G for square cribs plotted against the crib width D.

show the same behavior remains to be seen. The experimental work will require rather difficult tests with large areas but the results are needed for a better understanding of the burnout process comprising a part of the spread mechanism of wind-driven fires discussed in section V.

III. THE EFFECT OF STICK SIZE AND STICK SPACING ON THE RATE OF SPREAD OF CRIB FIRES

Fuel particle size and fuel particle spacing are two of a group of wood crib variables which have a marked effect on the burning rate and rate of spread of fire through wood cribs. The ignition time and burn-out time for small fuel particles are less than those for large particles. Increasing the stick spacing in a fuel bed increases the transmission of radiant heat in the direction of unburned fuel. However, if the spacing is too great, a tier of unburned sticks may not receive enough heat for ignition and the crib will not support a spreading fire. Also, if the sticks are too closely spaced, sustained burning will not be possible because of restricted air flow. Between these limits is the range of spacings in which sustained fire spread is possible. The actual limits, or the range of spacings, may depend on other crib variables such as moisture content.

Bryan (1943) reported that the burning time in wood cribs varied as the 3/2 power of stick size. The work of Fons et al (1963) indicated that the 3/2 power relationship is not valid in cribs of closely spaced sticks where the volume of the voids is equal to or less than the volume of the fuel. Fons et al (1960) reported the effect of fuel size on rate of fire spread in cribs with a fuel spacing of 1¼ inches. His results indicated that rate of spread varies inversely as the 1/2 power of stick size.

To study the effect of stick size and stick spacing on rate of spread, thirty white fir cribs were constructed with four different stick sizes and seven different spacings. Wood density and moisture content (about

10.5 percent) were kept constant. The overall dimensions of the cribs were about the same--height 8 inches, width 10 inches, and length 40 inches. The experimental conditions and results are given in tables 4 and 5 of the Appendix. A complete description of the equipment and procedures was given by Fons _et al_ (1962). The cribs were ignited at one end with about 15 milliliters of n-hexane. After a brief initial buildup period, the fires burned through the cribs at a constant rate.

However, when the stick spacing in the cribs exceeded 2.0 inches, the fires began to exhibit an undulating effect in the rate of spread as the flames passed from one lateral tier of sticks to another. The magnitude of these undulations increased with spacing. The tabulated rate of spread values for these fires were averaged over a long time interval so do not reflect the flame undulations. In figure 4 rate of spread is plotted against stick size for different stick spacings. The same data are shown in figure 5 with rate of spread plotted against stick spacing for different stick sizes. Although for some of the curves there is considerable scatter of the data, these figures show that rate of spread varies approximately as $d_o^{-.6} S^{.9}$ where d_o is the stick size and S the stick spacing or distance between sticks.

To estimate the heat received by sticks in the interior of a crib as the burning zone approaches, a calorimeter device was placed in the crib. It consisted of a blackened horizontal 1/4-inch copper tube with water flowing through at a constant rate. Two thermocouples were placed in the tube to measure the temperature of the water before it entered and after it left the crib. The tube was perpendicular to the direction of fire spread and

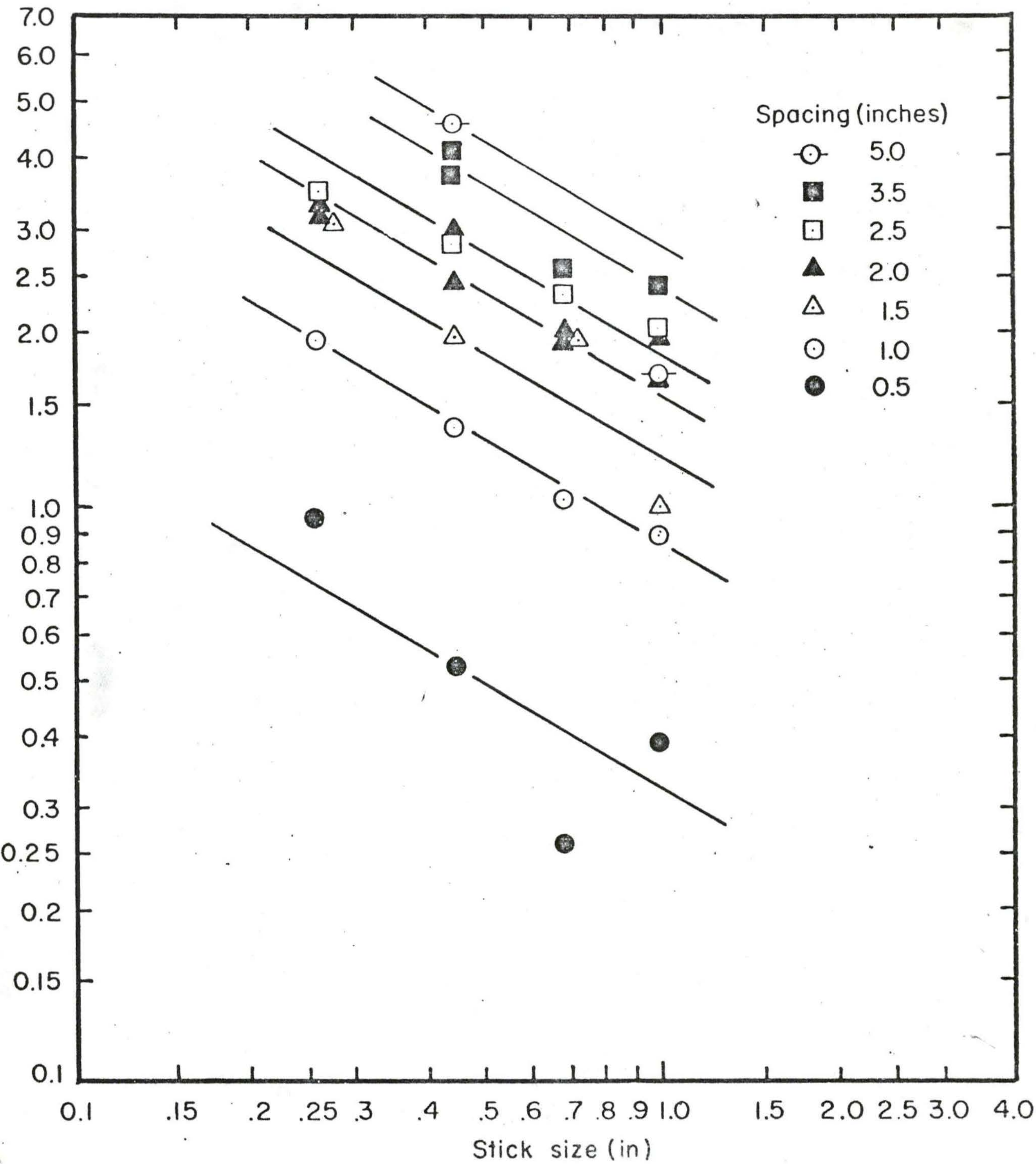

Figure 4.--The relation of rate of fire spread to stick size for different stick spacings in cribs of white fir wood.

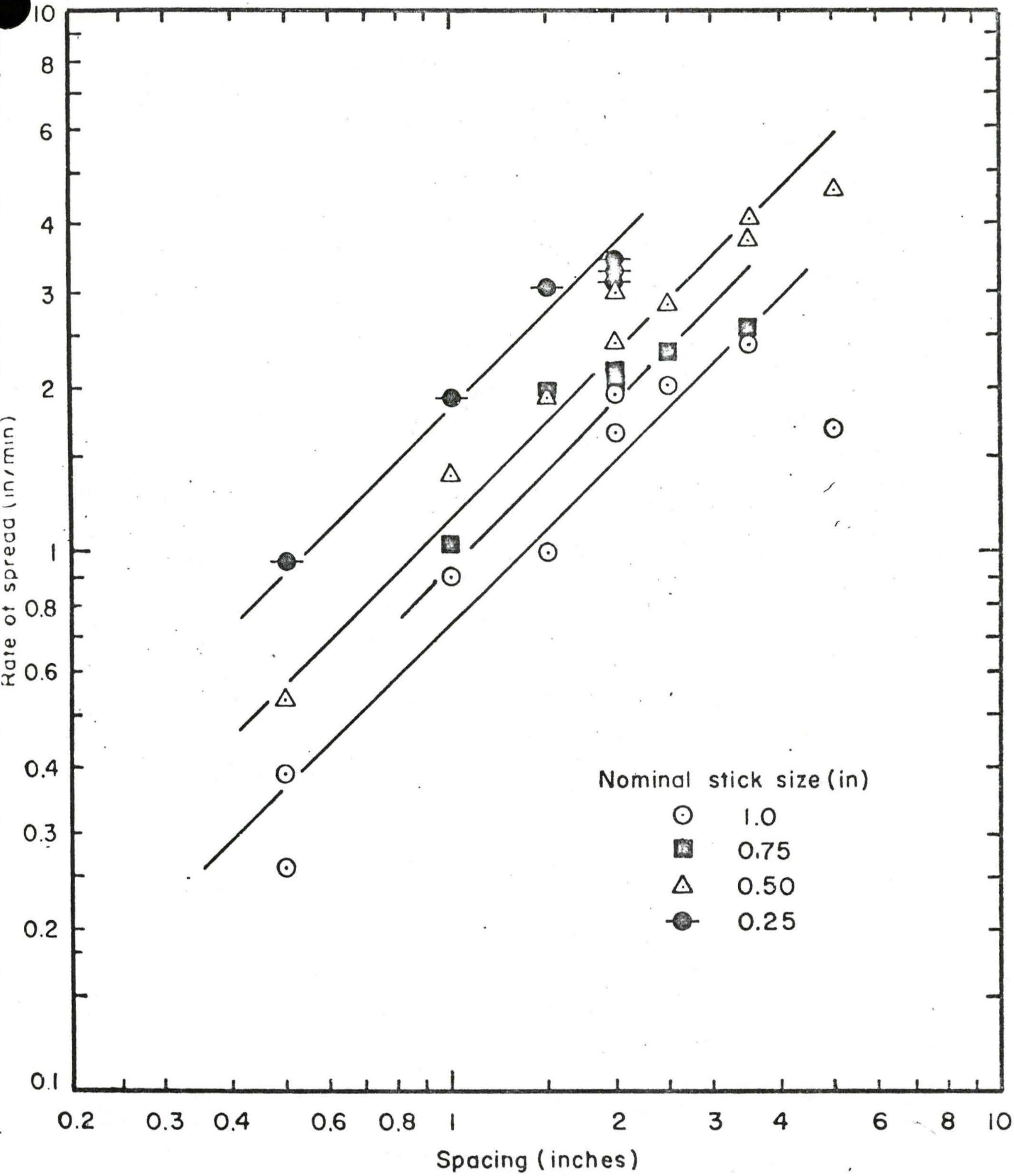

Figure 5.--The relation of rate of fire spread to fuel spacing for different stick sizes in cribs of white fir wood.

was in the horizontal plane separating the upper third and the lower two-thirds of the crib. In the longitudinal direction it was located about two-thirds of the way through the crib. The rate of heat received by the tube can be expressed as

$$I = C_p \dot{M} \Delta t / A_t$$

where I is the rate of heat received per unit area of tube, C_p the specific heat of water, $\dot{M}$ the rate of mass flow of water, Δt the temperature rise, and A_t the area of the tube in the crib. The heat rate estimates ranged from 20 to 70 Btu/ft^{2}min just before the approaching flames contacted the tube.

IV. THE EFFECT OF WIND ON THE RATE OF SPREAD OF CRIB FIRES

The effect of wind speed on the rate of fire spread in wood cribs with different spacings was studied by burning a series of cribs in a low-speed wind tunnel. The wind tunnel fan delivers a maximum of 40,000 cubic feet of air per minute and gives wind speeds from about 3 to 13 feet per second in the 8 x 8-foot test section. The air was recirculated during the test fires. To control its temperature and relative humidity, a part of this air (about 6,000 ft^3/min) was passed through a process air unit. This unit is part of the wind tunnel system and is equipped with 20 tons of refrigeration, heating coils, and steam spray nozzles.

Wind speeds in the test section are controlled by manually operated dampers on the discharge side of the fan. Before reentering the wind tunnel, the air passes through a 30,000 cubic foot settling chamber in which the speed of the air is reduced to near zero. The 16-foot square wind tunnel entrance to the settling chamber is equipped with both vertical and horizontal straightening vanes to reduce turbulence in the 8 x 8 x 18 foot test section.

A combustion table 1.25 feet high, 3.5 feet wide, and 12 feet long was mounted in the center of the test section for supporting the cribs. The ignition end of the cribs was placed 4.0 feet from the upwind edge of the table. They were ignited in the same manner as described by Fons et al (1962) except that the ignited crib was sheltered from the wind stream for a short time until the flames were well established. The fire was then allowed to spread freely through the crib with the wind.

In the laminar flow of the test section, the flames had a smooth "unnatural" appearance. It was found that a vertical 2-inch barrier placed across the leading edge of the table introduced enough turbulence to give the flames a normal appearance. The curves in figure 6 show the vertical wind speed profiles over the center line of the combustion table 4.0 feet from its leading edge. These measurements were made without the barrier for three different wind speeds. Similar curves with the barrier in place are given in figure 7. The barrier produced a turbulent layer about 15 inches deep at the position where the profiles were determined.

A total of 19 cribs were burned in the series of tests. They were constructed from 1/4-inch white fir sticks with spacings of 1/2, 1-1/2, 2-1/2, and 4-1/2 inches. Cribs 3 feet long were used for the tests at low wind speeds and cribs 6 feet long for the tests at higher speeds. The cribs all had about the same heights and widths and the density of the wood from which they were constructed varied from 22.5 to 25.2 pounds per cubic foot. Brown wrapping paper treated with diammonium phosphate fire retardant solution was glued to the sides and leeward end of the crib to simulate greater crib width and length by restricting the flow of air into the crib.

The experimental conditions and results for these test fires are given in table 6 of the Appendix. Rate of fire spread was measured by tracking the flame zone with a one-power telescopic gunsight mounted on a trolley free to move parallel to the wind tunnel on an aluminum I-beam. The angle of tilt of the flame and flame length were determined from photographs. Wind speeds were measured with a Pitot tube mounted 2.75 feet above the center line of the combustion table and at a horizontal distance of 3.5 feet downwind from the 2-inch barrier.

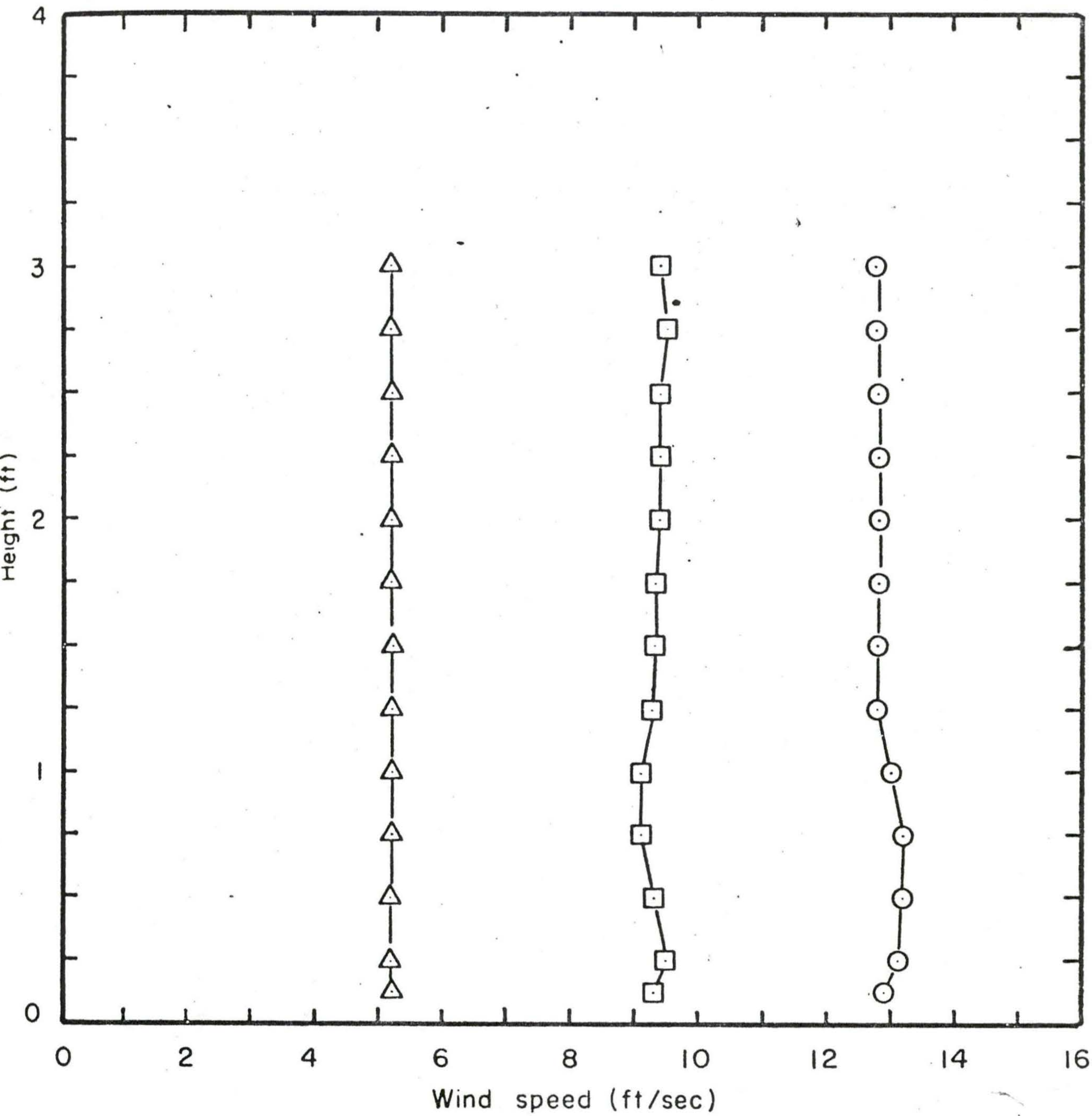

Figure 6.--Wind speed profiles above the combustion table in the test section of the wind tunnel with wind speeds of 5.5, 9.8, and 13.1 ft/sec., without barrier.

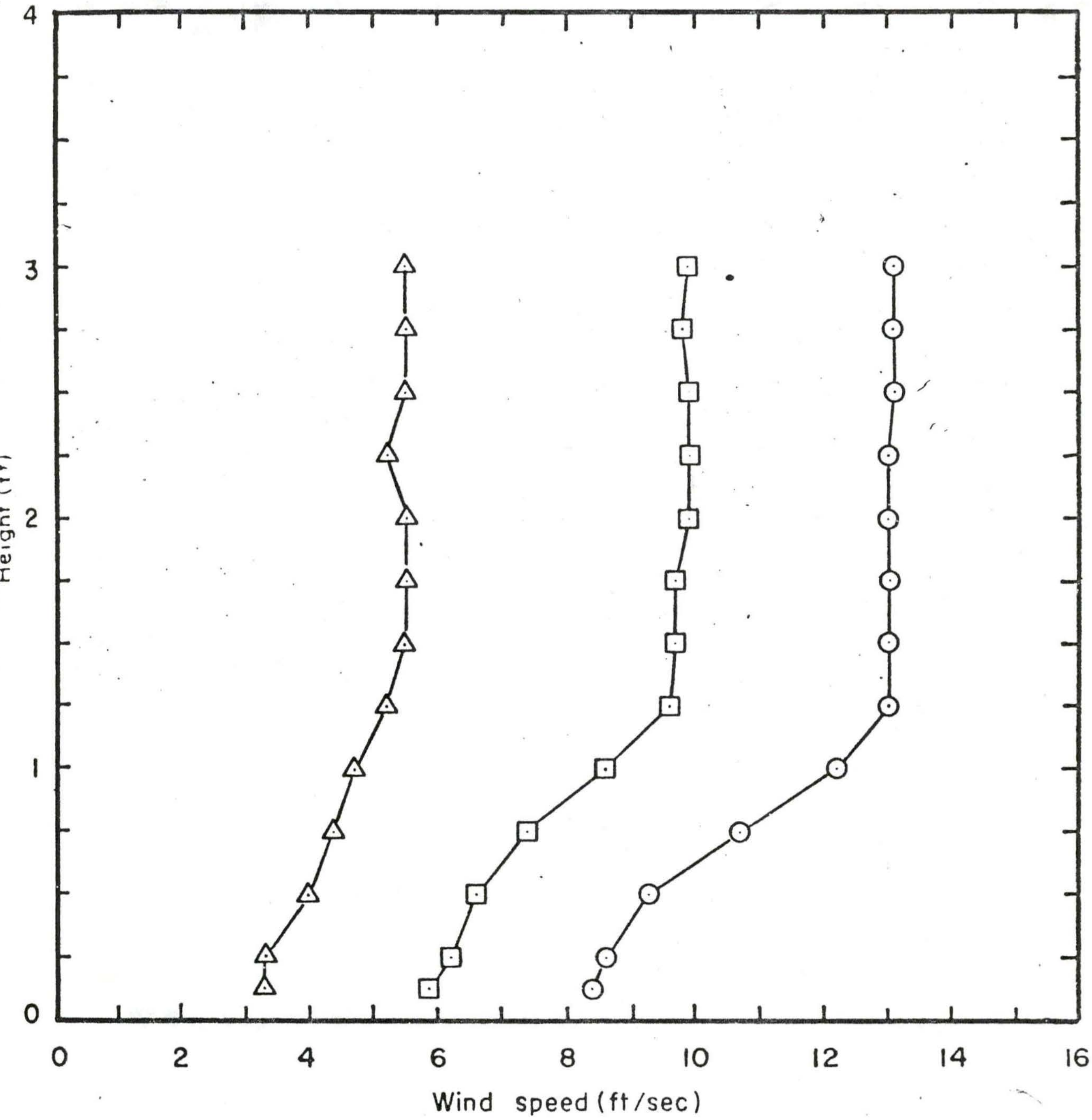

Figure 7.--Wind speed profiles above the combustion table in the test section of the wind tunnel with wind speeds of 5.2, 9.4, and 12.8 ft/sec. A barrier at the leading edge of the combustion table creates a turbulent layer approximately 1.25 feet deep.

Rate of spread for the crib fires is shown plotted against wind speed for different stick spacings in figure 8. When extended, these curves have a nearly common origin on the horizontal axis and can be represented by the empirical equation

$$R = k(u + u_o)S^{.9}$$

in which K and u_o are constants. The constant u_o has the dimensions of velocity. It is doubtful that fires in other types of fuel beds will in general show a linear relationship between rate of spread and wind speed.

When the first cribs were burned in the wind tunnel it was found that the flames had quite a different appearance and structure than for a fire spreading through a crib in calm air. Depending on the speed of the wind and the rate of convective heat output, the flames and convection column were tilted at an appreciable angle from the vertical. For a short distance downwind from the leading edge of the burning zone the flames appeared to be in contact with, or very close to, the upper surface of the crib. For a somewhat greater distance, random fingers of flame would descend from the lower surface of the tilted flame front to make momentary contacts with the upper surface of the crib. Also, unburned gases appeared to flow in a horizontal direction within the crib and would well up through the surface openings ahead of the burning zone. At the higher wind speeds these gases would ignite and form a small secondary fire about 10 to 16 inches ahead of the main burning zone. Eventually the area between the two fires would

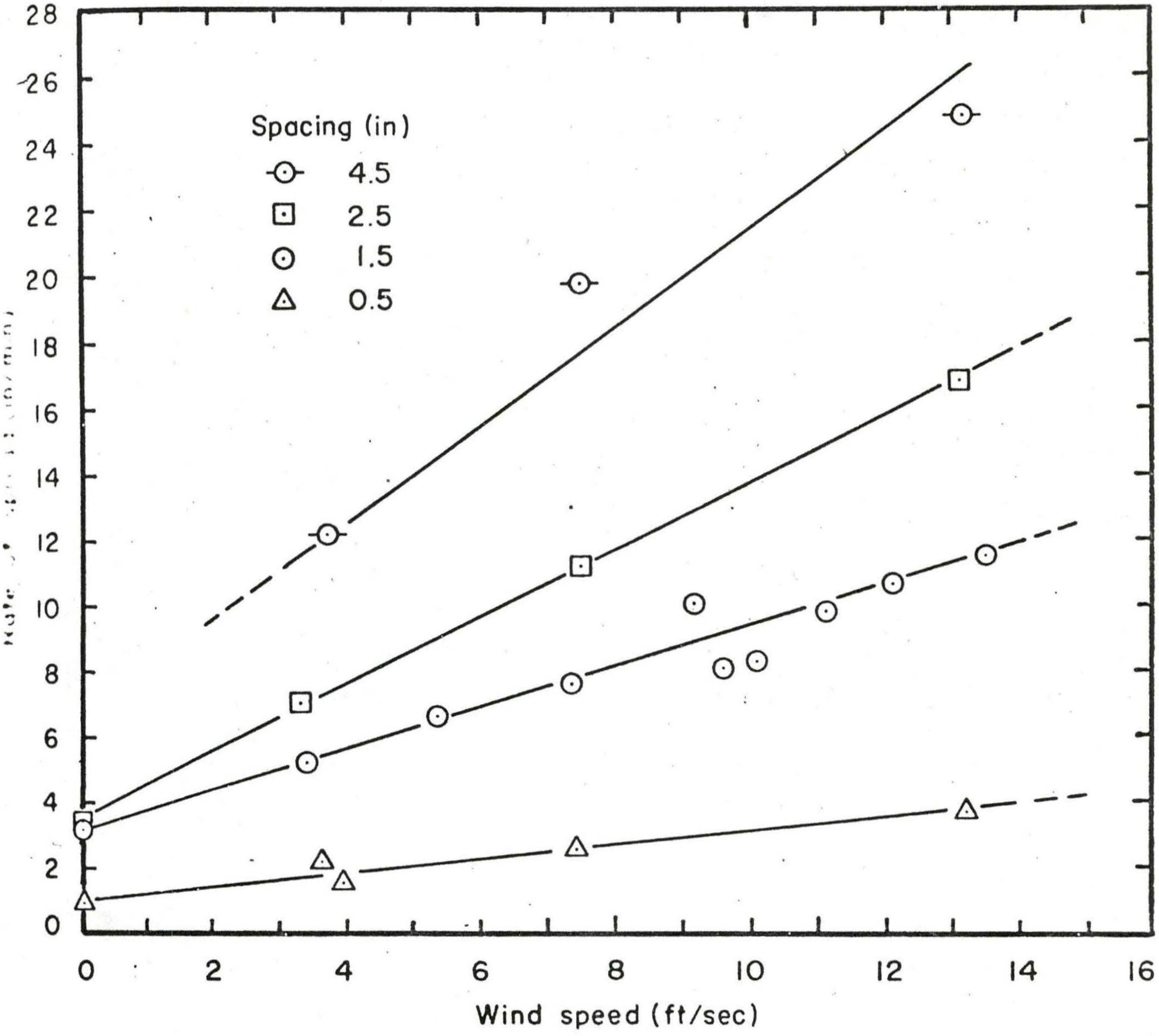

Figure 8.--The effects of wind speed and stick spacing on rate of fire spread in cribs of white fir wood.

ignite to form a single fire. This behavior made it difficult to identify the burning zone and to obtain the rate of spread. It is doubtful that the fires reached a steady-state even for the 6-foot cribs, although the main flame front would travel through the crib at a nearly constant rate.

V. THE MECHANISMS OF FIRE SPREAD

The flame front behavior which occurred when the cribs were burned in a wind stream was examined in greater detail by using a liquid fuel fire in a series of tests at different wind speeds. The turbulence producing barrier was kept in place. A pool of burning ethyl alcohol 12.7 inches square replaced the burning cribs. The upper surface of the pool at the time measurements and observations were made was about 0.5 inch below an extended horizontal surface surrounding the pool. On the downwind side of the pool a series of small tufts of loose cotton fibers were placed at 2-inch intervals. They were about 0.5 inch above the horizontal surface and located on a line which passed over the center of the pool in the direction of wind flow. When suddenly enveloped by a hot gas, the ignition time for these fibers was very small--probably only a few hundredths of a second. Their sensitivity to a sudden pulse of high temperature gas made them good detectors of the random fingers of flame descending from the under surface of the tilted flame front. Three 30-gauge chromel-alumel thermocouples were placed 1.0 inch above the horizontal surface and at distances of 4, 10, and 16 inches from the edge of the burning pool along the same line as the cotton tufts. The wind speed, as measured 2.75 feet above the horizontal surface, was constant for each test and ranged from 0 to 13.3 feet per second for the series.

In each test 2.39 pounds of alcohol were burned. The curve showing the rate of alcohol weight loss with time is given in figure 9 for zero wind speed. The alcohol probably reached its boiling temperature near the end of the burning period when the curve flattened out, thus indicating

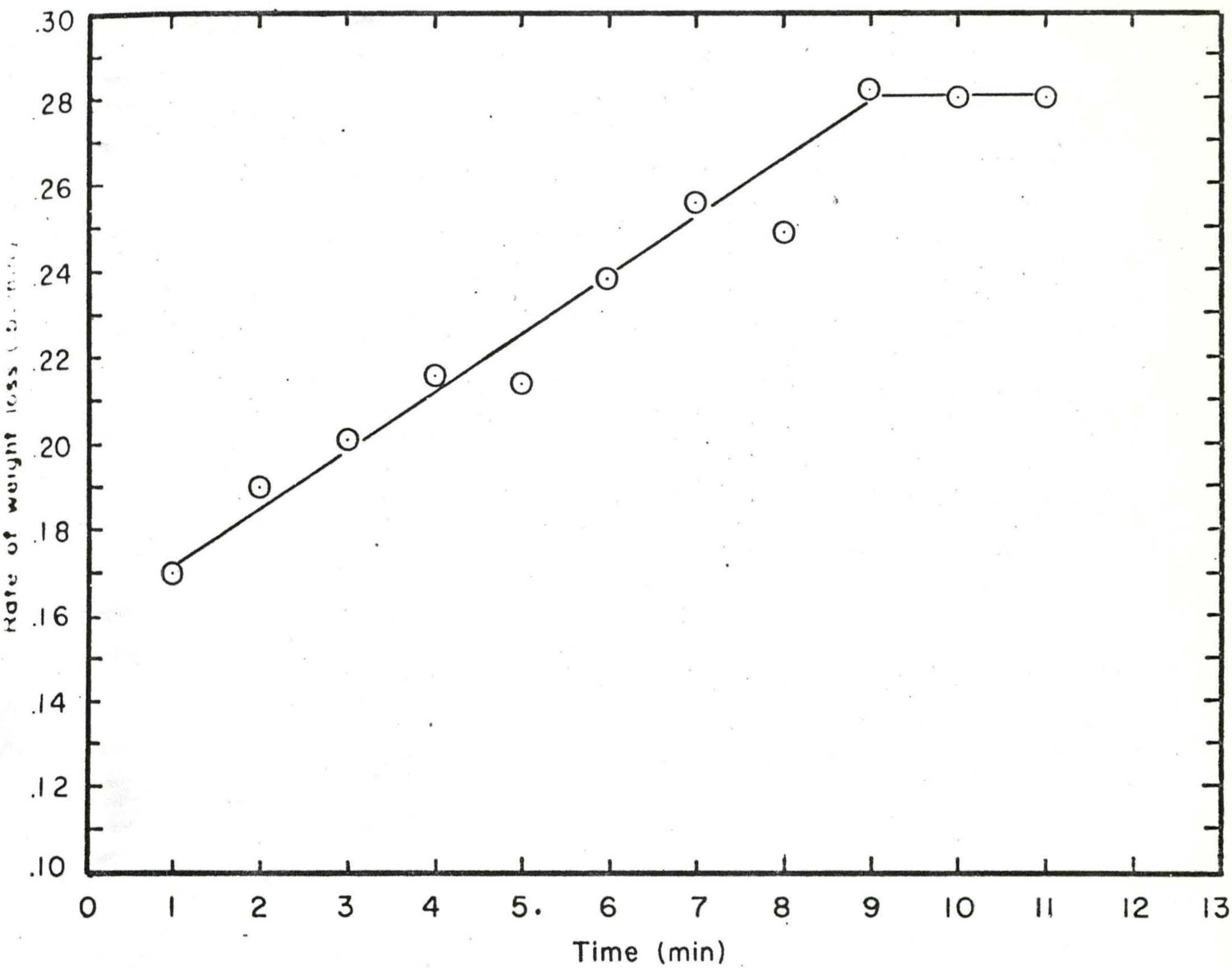

Figure 9.--The rate of weight loss for a 12.7-inch burning pool of ethyl alcohol is plotted against time. The pool was burned in still air.

a maximum constant burning rate. This was considered the significant rate from the standpoint of the ignition of the cotton tufts, so the maximum rate for each test was used in computing the rate of convective heat output. For all tests the burning time for 2.39 pounds of alcohol appeared to be nearly independent of wind speed. For this reason the burning rate curve was determined only for zero wind speed and the curves were assumed to be similar at other speeds. This afforded a simple method for estimating the maximum rate from the easily determined average rate. It was assumed that the rate of convective heat output was 80 percent of the total rate and that the low heat value of the alcohol fuel was 11,600 Btu per pound.

In the first test, which was made at zero wind speed, cotton tufts near the horizontal surface failed to ignite at a distance of 0.5 inch from the edge of the burning pool. On the next test (wind speed 3.7 feet per second) the tufts were ignited out to a distance of 16 inches. Table 1 shows the ignition distance of the cotton tufts, rate of convective heat output, and the dimensionless convection number N_c for the different wind speeds. The ignition distance is also shown in figure 10 as a function of wind speed. The convection number is a criterion of similarity between convection columns and will be discussed in section VI. Table 2 shows the average temperature and the temperature extremes of the rapidly fluctuating thermocouple readings. Owing to the appreciable time-lag of the thermocouples, the actual range would be somewhat greater than the thermocouples indicated. Even though the rate of heat output was nearly constant throughout the series of tests, the flame length increased from about 2.0 feet at zero wind speed to about 3.5 feet for the highest speeds. The angle of flame tilt is not shown for different wind speeds but at a wind speed of 3.7 feet per second it was

Table 1.--The rate of convective heat output, the ignition distance of the cotton tufts, and the convection number N_c are shown for wind speeds from 0 to 13.3 feet per second. The air temperature was nearly constant at 74°F. during the tests.

Wind speed (ft/sec)	Rate of convective heat output (Btu/sec)	Ignition distance (feet)	N_c
0.0	39.1	0.0	∞
3.7	37.2	1.33	2.34
5.4	35.4	1.42	0.72
7.6	37.2	1.83	0.27
10.9	38.1	2.17	0.10
13.3	39.1	2.08	0.05

Table 2.--The mean temperatures and the range of extreme temperatures given by thermocouples for the pool fires are shown for the different wind speeds and at distances of 4, 10, and 16 inches from the leeward edge of the burning pool.

Wind speed (ft/sec)	Mean temperature (°F)			Temperature extremes (°F)		
	4 in.	10 in.	16 in.	4 in.	10 in.	16 in.
0.0	143	106	104	130- 160	101- 112	93- 114
3.7	1500	584	186	1210-1720	223- 966	141- 359
5.4	1460	862	208	1180-1660	475-1340	162- 361
7.6	1460	1260	497	1090-1670	877-1650	375- 715
10.9	1390	1280	714	837-1700	807-1670	510-1030
13.3	1390	1310	852	1030-1660	875-1650	550-1260

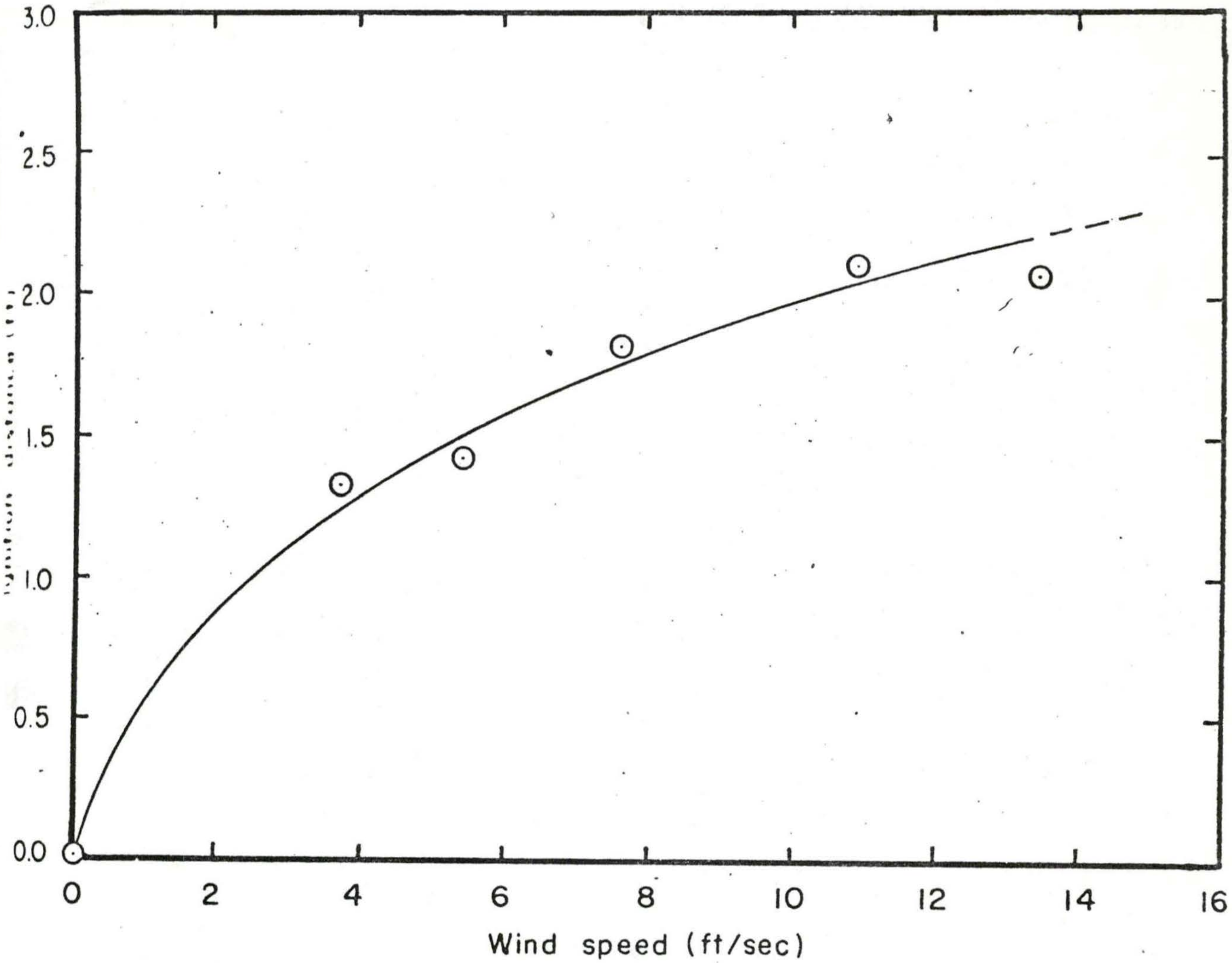

Figure 10.--The maximum distance at which cotton fibers were ignited downwind from the edge of a square pool of burning alcohol plotted against wind speed.

approximately 55 degrees from the vertical for the upper part of the flame. It increased with increasing wind speed and reached a value of nearly 80 degrees at the highest speeds.

Radiation appeared to play a minor part in the ignition of the cotton tufts. This is indicated by the low mean temperature of the thermocouple at the 16-inch distance (this was also the ignition distance) for a wind speed of 3.7 feet per second. Also, it was possible to see the ignitions take place when darting segments of flame contacted the tufts.

The solid lines in the diagrams in figure 11 represent vertical cross-sections of flame zones in a plane parallel to the direction of the wind. With the exception of diagram A, these cross-sections were drawn from photographs of the pool fires. The dotted lines illustrate the estimated position of the associated convection columns. Diagram A is a hypothetical cross-section of a fire in a light wind as it has been visualized in the past. The flame and convection column are tilted over but it has been assumed that the slight indraft which exists on the leeward side of the flame gives the lower front surface of the flame the shape indicated. Diagram B is a cross-section of a pool fire when the wind speed was 3.7 feet per second. The shape of the lower front surface of the flame is entirely different than indicated in diagram A. The lower flames leave the front edge of the burning pool in a forward horizontal direction[1/] and

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1/ Preliminary theoretical calculations indicate that the horizontal speed of the flames in this region may be greater than the speed of the wind. If so, then wind converts a flame front into a form of jet. However, this has yet to be determined experimentally.

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remain close to the surface for some distance before the buoyant forces cause them to start traveling upwards. Ahead of the region where the

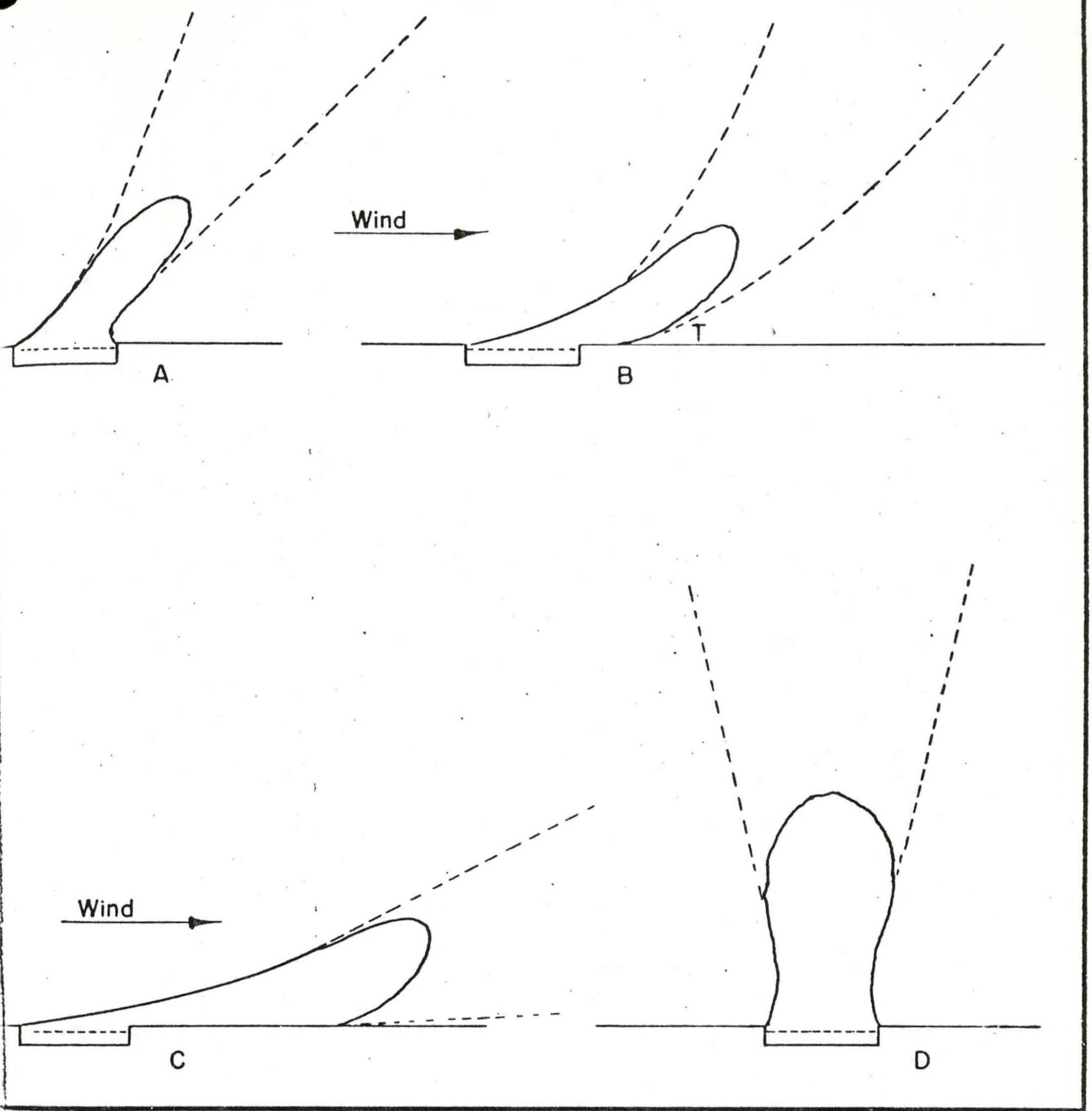

Figure 11.--Cross-section diagrams are shown for the flame zones and convection columns over burning areas. Diagram A shows the usual concept of the deflection and shape of the flame zone (solid line) and of the convection column (dotted line) for a burning area in light wind. Diagrams B, C, and D are the observed cross-sections of the flame zones and estimated convection columns for a 12.7-inch square pool of burning alcohol with wind speeds of 3.7, 13.3, and 0.0 ft/sec, respectively.

flames are near the surface is a region sheltered from the main wind stream which is designated as T in diagram B. It is in this region that the random turbulent fingers of flame descend to the surface. There should be a slight indraft toward the flames within this region also as was indicated for diagram A, but it would not reach the edge of the burning pool. An extension of the center line of the upper part of the convection column would intersect the horizontal at a point well ahead of the burning pool. It is usually assumed that this point probably would be near the center of the burning area as would be the case in diagram A. Diagram C is similar to B except that the wind speed is much higher (13.3 ft/sec) and the flame is nearer the horizontal. Diagram D represents the flame and convection column over the burning pool when the wind speed is zero. A slight inflow from all sides tilts the flame inward near the horizontal surface.

Although only a limited number of tests of this type have been made, we believe the burning pool experiment illustrates one of two important interacting physical processes which together comprise a mechanism that may control the spread of the majority of all forest fires. These are the fires that are driven by the wind. The nearly continuous envelopment of the surface fuel for some distance ahead of the leading edge of the active burning zone plus random flame contacts at greater distances ignite the surface fuels. This effect would be magnified for fuels such as brush or tall-standing cured grass which would be penetrated by the jet-like flames. The second process in the mechanism concerns the rate of burnout of the fuel layer after the surface has been ignited and should have a marked effect on the rate of spread. The presence of long flames ahead of

the burning zone requires a short burnout time after the surface fuels have been ignited. In turn, a short burnout time would involve the downward rate of heat flow and the characteristics of the heterogeneous fuel layer including its moisture content. Secondary ignitions would increase the burnout rate when burning fragments of fine surface fuel fall through openings in the fuel layer and ignite fine fuels below. The rate of spread resulting from these two processes should be increased considerably by the presence of fine fuels, both on the surface and within the fuel layer. This fine material is present in the majority of forest fuel types.

Fire research workers have always felt that the preheating of surface fuels by radiation from the flame front was a dominant factor in the ignition of unburned fuel. A corollary to this idea has been the belief that radiation was involved in the effect of wind on fire spread in that flames slanted by the wind radiate more effectively to the fuels immediately below. We do not doubt the correctness of this assumption insofar as increased radiation is concerned, but our preliminary series of tests indicate that the contribution of flame radiation to the ignition of new fuel is small compared to that of flame envelopment and flame contact for wind-driven fires. Possibly the contribution of radiation increases with increasing fire intensity. Preheated fuels would have a somewhat shorter ignition time and under intense radiation the random flame contacts could give a type of pilot ignition.

Wind-driven fires have a wide range of rate of spread values but most of them are in the range between 0.1 and 2.0 feet per second. Fires traveling up steep slopes can move considerably faster than this but may have a similar flame front structure. They have not as yet been studied on a laboratory scale.

There is one type of fire for which surface ignition by hot gas envelopment (or random flame contact) plays little part. This type has a very low rate of spread (about 0.02 to 0.04 foot per second in mixed grass and pine needle fuel) and includes fires burning in still air and also those which spread against the wind. Radiative heat transfer in a horizontal direction within the fuel layer from the burning zone appears to be the dominating ignition process. The model proposed by Emmons (1964) should apply to this type of fire. The spread mechanism represented by this model also includes the burnout process but not in quite the same way as the surface ignited fuels in wind-driven fires.

The spread mechanisms are not well understood for one of the most important types of fires. These are the major convective fires or so-called "blowups." A detailed discussion of these fires is outside the scope of this report but their possible mechanisms of spread will be considered briefly. The characteristics of these fires were discussed by Byram (1959). Their sustained rates of spread are usually from 1.5 to 6.0 feet per second but may be considerably greater during erratic surges. One of their most prominent features is the convection column which may tower to a great height or it may be terminated, or fractured, by a layer of high-speed winds several thousand feet above the earth's surface. In either case the column appears to be of the free convection type although the wind stream may distort its shape and pattern of internal motions somewhat from the free convection forms. The two processes suggested as the mechanism of spread for the ordinary wind-driven fires should also operate in the same way for fires of a much higher intensity. For the major convective fires, however, there appears to be a second mechanism which operates independently of the first. It can also be broken down into two key processes. One is the transport of burning material which is carried aloft by the strong updrafts

in the convection column (or columns). On a large scale embers falling from the convection column may reach the proportion of an ember shower which can ignite extensive areas well ahead of the advancing fire front. The second process concerns the rate of burnout of the ember-ignited fuel and is analogous to the second process in the spread mechanism for wind-driven fires.

Fire spread by ember transport may be the most important mechanism for the major convective fires but this is not certain. Furthermore, there may be other mechanisms involved. It is known that there are complex convective phenomena in and near the fronts of major fires. These are not well understood but they could contribute to both the rate of spread and the erratic behavior of these fires. For example, intense tornado-like whirls can form in the burning zone which have stronger vertical updrafts than could occur in any ordinary convection column. We have measured updraft velocities of more than 40 feet per second in laboratory models of fire whirls which were only about 12 feet in height. Possibly on a larger scale these vortices may be one cause of ember showers. Another type of vortex associated with these fires resembles the tornado in appearance. It forms at a considerable height on the underside of the tilted convection column. Sometimes these pendulous funnel-shaped structures may form at a considerable distance ahead of the fire front (occasionally a mile or more). Their effect on fire behavior is not known but is probably less than for vortices in or near the burning zone.

There is one factor which indicates that the mechanism involving ember transport (and possibly other processes related to large buoyant forces)

dominates the behavior and spread of the major high intensity fires. This is the magnitude of the dimensionless convection number N_c and its variation with height above the earth's surface. For most wind-driven fires N_c is usually considerably less than unity near the earth's surface and decreases rapidly with height. For "blowup" fires, however, N_c appears to be greater than unity near the surface and either remains constant with height or increases with height. N_c will be discussed briefly in the next section.

VI. CONVECTION COLUMN SCALING RELATIONSHIPS

In recent years there have been numerous papers describing theoretical and experimental work on convection columns over point and line heat sources in still air so the scaling relationships for free convection over such sources are well understood. On the other hand, there have been relatively few papers dealing with convection over heat sources in a wind field. One of the most recent is a paper by Pipkin and Sliepcevich (1964) describing a study to determine the effect of wind on the bending of buoyant diffusion flames.

Although its significance has yet to be determined experimentally, a promising parameter for studying convection columns in a wind stream is a dimensionless group which will be designated as the convection number N_c. For a fire, or other heat source, in the form of a long line perpendicular to the direction of the wind, this number takes the form

$$N_c = \frac{g\, Q_c'}{C_p T_o \rho_\infty u^3} \qquad (1)$$

where g is the acceleration due to gravity, Q_c' is the rate of convective heat output per unit length of line heat source, C_p the specific heat of air at constant pressure, T_o the absolute temperature of the air at the earth's surface, ρ_∞ the density of the atmosphere at some height z above the earth's surface, and u the speed of the wind at height z. N_c should determine convective similarity between columns. For example, convection columns over line heat sources of different strengths and in

wind streams of different velocities should have the same angle of tilt from the vertical if N_c is the same in each case. For a point source N_c takes the form

$$N_c = \frac{g\,Q_c}{r\,C_p T_o \rho_\infty u^3} \tag{2}$$

where r is the radius of the convection column at height z and $\dot{Q}_c$ is the total rate of convective heat output of the point source. Equations (1) and (2) are written for an isentropic compressible fluid, such as the atmosphère when the vertical temperature gradient is equal to the dry adiabatic gradient. However, they remain unchanged for an isothermal incompressible fluid. They take more complex forms for non-isentropic compressible fluids and non-isothermal incompressible fluids.

The value of N_c for each of the pool test fires is shown in table 1 but in each case the values probably have significance only in the upper part of the convection columns for heights which are large compared to the dimensions of the area source. The computations were based on equation (1), but with z held constant equation (2) would have given the same relative values of N_c between fires. Large values of N_c indicate steep convection columns and small values indicate sharply bent over columns. Owing to the disturbing effect of the wind tunnel walls and ceiling, no attempt was made to obtain information on the form of the convection columns for the pool fires. For the fire burned with a wind speed of 3.7 feet per second, N_c was 2.34. This is a relatively large value and a fairly steep convection column could exist above the flame zone (in the absence of the wind tunnel

ceiling). Updraft velocities and patterns of internal motion might be similar to those for free convection. For the fire which burned with a wind speed of 13.3 feet per second, N_c was only 0.05. It is doubtful that a convection column could exist in this case. It would more likely take the form of an upward slanting plume with its lower boundary maintaining contact with the horizontal surface downwind from the fire. The structure and motions within this plume should be entirely different than for the free convection-type column.

For area fires, values of N_c computed from equations (1) or (2) are probably of doubtful significance in the flame zone and the lower convection column--at least at heights small compared to the dimensions of the burning area. For example, even with a value of $N_c = 2.34$, the flames leave the forward edges of the pool in a horizontal direction (fig. 11B). Scaling relationships for describing dependent variables such as the shape of the lower extremity of the convection column and velocities in this region are probably very complex for area heat sources in wind.

VII. CONCLUSIONS

Although test fires in square cribs were limited to a narrow size range of small cribs, the results show that within this range the relationship between unit area burning rate and burning area of the cribs parallels that reported for fires in pools of liquid hydrocarbon fuels. Tests are needed in beds of solid fuel with larger areas than used thus far. Surface ignition should be used and the effects of wind included.

The effect of stick spacing on rate of fire spread in cribs of 1/4-inch sticks appeared to be about the same for cribs burned both with and without wind. However, it is doubtful that much information on the burning characteristics of fuel beds with wind can be gained from test fires spreading in cribs without wind because of the marked differences in the basic spread mechanisms. Even a wind of only 2 feet per second produces an ignition process in model fires that is absent in fires with no wind.

Flames coming in contact with the surface of a crib burning with wind extend the combustion zone in an erratic way. For a crib six feet or less in length, ignition of the surface of the crib ahead of the main burning zone does not appear to greatly affect the rate of spread of the main flame front. However, the fire does not appear to reach a steady-state in a short crib. Cribs 16 feet or more in length may be required to obtain steady-state fires.

Liquid fuels are more satisfactory than solid fuels for studying the effect of wind on the structure of flame fronts. Gaseous fuels might be

even better for some kinds of tests. Even on a small scale, pool fires in wind illustrate a flame contact ignition process which is probably an important part of the spread mechanism for wind-driven fires. Results of tests using liquid fuels could have considerable bearing on the design of later experiments with beds of solid fuel.

VIII. FUTURE WORK NEEDED

The development of a quantitative model of fire spread for wind-driven fires will depend on the solution of a sequence of problems. First is the identification of the different physical processes which comprise a given mechanism of fire spread. Next is developing an understanding of the individual processes, determining the variables upon which they depend, and investigating the nature of their interactions. The next step would be an analysis to establish the mathematical framework of a quantitative model of fire spread. The high-intensity convective fires would not be included for the time being.

The results of both the crib fires and the pool burning tests in the wind tunnel show the need for a more intensive study of the effect of wind and slope on the structure of flame fronts. This study would include determining velocities and flow patterns of gases in the flame zone as well as the air flow patterns in the vicinity of the flame front. Tests should be made with areas of different shapes and sizes, different burning rates per unit area, and with variable burning rates (burning rate gradients) across the areas. Wind speeds would range from about 1.0 to 12 feet per second. Tests should also be made on sloping plane surfaces without wind. The angle of the surface with the horizontal for the different tests would range from 0° to 40°. An attempt should be made to identify dimensionless groups which would have the same significance for scaling in the regions just over an area heat source that the convection number appears to have for the upper convection column.

A closely related study would deal with the rate of burnout of beds of solid fuel after ignition over their entire area. This study would be an extension of the work described in Section II except that much larger areas should be included and ignition would be from the top rather than from the bottom of the fuel bed. Tests would be made both in still air and with wind.

It is expected that a few tests in the wind tunnel with long cribs (up to 16 feet or more in length) will result in steady-state fires, except possibly at the higher wind speeds.

The work described in Section IV on the effect of wind on the rate of spread should be extended to cribs of a somewhat different structure than used in the tests thus far and also to heterogeneous beds of solid fuel which contain some fine material. The cribs should be longer, wider, and perhaps only one-half as deep as the present cribs. The quantitative relationships for describing the effect of wind on fire spread should be easier to establish when more is known about the structure and behavior of fire fronts and when more progress has been made on the scaling relationships over simple area heat sources.

NOMENCLATURE

A_t	Area of copper tube in the crib	ft^2
C_p	Specific heat	Btu/lb °F
d_o	Initial thickness of fuel sticks	inches
D	Width of square cribs; depth of flaming zone in direction of fire spread	ft, inches
g	Acceleration due to gravity	ft/sec^2
G	Burning rate per unit area	lbs/ft^2 min
h_b	Height of crib	inches
I	Heat rate received per unit area	Btu/ft^2 min
L	Length of flames	inches
L_b	Length of crib	inches
$\dot{M}$	Mass flow rate of water	lbs/min
M_f	Moisture content of wood based on bone dry weight	percent
n	Exponent	
N_c	Convection number	
Q	Rate of burning	Btu/sec
Q_c	Rate of convective heat	Btu/sec
Q_c'	Rate of convective heat per unit length of line source	Btu/ft sec
R	Rate of fire spread	in/min
S	Fuel stick spacing	inches
t_o	Air temperature	°F
t_s	Stack gas temperature	°F
u	Wind speed	ft/sec
$\bar{U}$	Average wind speed	ft/sec
w_b	Width of crib	inches

W_f	Weight of fuel (bone-dry)	lbs
W_o	Loading (bone-dry weight of crib per unit area)	lbs/ft^2
Δt	Temperature change	°F
θ	Time	min
θ_r	Burning time of fuel particles	min
ν_∞	Kinematic viscosity of air	ft^2/sec
ρ_b	Density of fuel bed, bone-dry	lbs/ft^3
ρ_f	Density of fuel, bone-dry	lbs/ft^3
ρ_∞	Density of air	lbs/ft^3

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APPENDIX

The experimental conditions and results for the crib fires are given in tables 3 to 6. The symbols in the tables are explained in the nomenclature.

Tables 4 and 5 include three fires (66, 67, and 68) which were constructed with different arrangements of the fuel sticks, so the results for these fires are omitted in the text.

The rate of spread values in figure 8 for zero wind speed are given in tables 4 and 5 (fires 72, 83, and 96).

Table 3.--Experimental conditions[1] and results for area fires in square cribs of white fir wood[2]

Fire No.	Fuel bed parameters[3]		Burning parameters		Dimensionless groups	
	D	W_f	$(dW_f/d\theta)_{max}$	G	$(GD/\nu_\infty \rho_\infty)$	$(D^3 g/\nu_\infty^2)$
	ft	lbs	lbs/min	lbs/ft^{2}min		x10^{-8}
D-1	0.190	0.11	0.059	1.63	415	0.0765
D-2	.274	.18	.112	1.49	547	.229
D-3	.358	.30	.176	1.38	662	.512
D-4	.527	.62	.304	1.09	769	1.64
D-5	.780	1.31	.703	1.16	1210	5.38
D-6	1.03	2.27	1.04	.99	1370	12.1
D-7	1.28	3.49	1.47	.90	1540	23.4

1/ Conditions of air were: temp = 83°F.; ν_∞ = 0.0102 ft^2/min; and ρ_∞ = 0.0731 lbs/ft^3

2/ Stick thickness d_o = 0.252 inch with a moisture content of wood M_f = 10.1 $\pm$ 0.1 percent and wood density ρ_f = 33.0 $\pm$ .3 lbs/ft^3

3/ Height of fuel bed h_b = 3.1 inches and stick spacing S = 0.75 inch

Table 4.--Experimental conditions for fires in cribs of white fir wood[1/] with different stick sizes and spacings

Fire No.	Room temp.[2/]	Fuel and fuel bed parameters									
	t_o	d_o	M_f	ρ_f	ρ_b	W_f	W_o	h_b	w_b	L_b	S
	°F.	In.	Per-cent	Lbs/ft3	Lbs/ft3	Lbs	Lbs/ft2	In	In	In	In
66	82	0.432	10.5	26.1	7.52	7.26	3.43	5.48	8.84	36.1	1.25
67	85	.432	11.1	26.1	7.07	7.17	3.23	5.48	8.94	35.8	1.25
68	83	.432	10.8	26.3	6.82	6.71	3.06	5.38	8.84	35.8	1.25
69	84	.443	11.3	25.9	4.99	7.39	3.00	7.22	10.22	34.6	2.0
70	81	.443	11.2	25.9	4.25	5.93	2.58	7.28	9.27	35.8	2.5
71	82	.261	10.8	25.6	3.21	4.32	1.98	7.38	9.25	34.0	2.0
72	82	.261	10.8	25.6	2.71	3.31	1.67	7.38	8.54	33.4	2.5
73	84	.680	10.9	25.2	5.88	12.04	4.04	8.25	10.22	42.0	2.5
74	84	.680	11.5	24.9	6.82	11.62	4.68	8.25	8.72	40.9	2.0
75	82	.989	11.0	24.7	8.73	20.69	3.58	7.94	9.96	51.8	2.0
76	73	.989	11.7	24.5	7.48	19.63	4.96	7.94	11.46	49.8	2.5
77	76	.443	8.9	26.1	3.32	6.07	1.95	7.16	12.27	35.9	3.5
78	72	.443	9.0	25.8	2.56	4.66	1.54	7.19	11.33	38.5	5.0
79	74	.989	10.7	24.9	4.84	15.84	3.21	7.94	12.97	54.9	5.0
80	76	.680	10.9	25.5	4.86	8.89	3.33	8.25	9.04	42.5	3.5
81	70	.989	10.4	24.5	6.24	14.48	4.15	8.00	9.97	50.4	3.5
82	67	.443	10.4	25.8	3.34	6.08	1.99	7.12	12.27	35.9	3.5
83	82	.261	10.5	23.6	3.77	4.83	2.28	7.25	9.07	33.7	1.5
84	85	.443	10.5	23.7	5.63	6.92	3.42	7.28	8.22	35.4	1.5
85	80	.680	10.3	23.2	7.54	14.26	5.19	8.25	9.40	42.1	1.5
86	86	.989	10.6	23.2	9.66	19.22	6.45	8.00	8.46	50.8	1.5
87	72	.443	10.5	23.3	4.46	6.65	2.70	7.28	10.22	34.6	2.0
88	76	.680	10.5	23.3	6.37	10.90	4.40	8.31	8.72	40.9	2.0
89	86	.261	10.2	23.6	3.04	4.01	1.81	7.19	9.30	34.2	2.0
90	90	.989	10.7	23.0	8.08	19.30	5.39	8.00	9.96	51.8	2.0
91	86	.680	10.8	23.2	9.63	16.95	6.57	8.19	9.08	41.0	1.0
92	84	.256	10.2	24.8	5.10	6.22	3.09	7.31	9.09	31.8	1.0
93	89	.989	10.4	23.2	11.79	24.52	7.78	7.94	8.94	50.7	1.0
94	84	.443	10.5	23.5	7.27	10.11	4.38	7.25	9.10	36.5	1.0
95	84	.680	10.3	23.3	13.26	23.08	9.12	8.25	8.94	40.8	0.5
96	76	.255	10.0	25.1	8.24	9.89	4.99	7.31	8.63	33.0	0.5
97	82	.443	10.4	23.5	10.77	14.97	6.48	7.25	8.93	37.2	0.5
98	72	.989	10.7	23.0	15.00	22.20	9.49	7.94	9.92	32.5	0.5

...te fir (Abies concolor)

...Average of readings taken before and after fire.

Table 5 .--Experimental results for fires in cribs of white fir wood with different stick sizes and spacings

Fire No.	Burning parameters			Flame dimensions		Heat rates		Stack[1/] gas conditions			
	θ_r	G	R	D	L	Q	Q_c	$\bar{U}$	Δt	t_s	ρ_s
	Min	$\frac{Lbs}{ft^2\ min}$	$\frac{In}{min}$	In	In	$\frac{Btu}{sec}$	$\frac{Btu}{sec}$	$\frac{Ft}{sec}$	°F	°F	$\frac{Lbs}{ft^3}$
66	4.3	0.79	1.61	6.9	31.8	45.5	20.4	24.0	15.9	98	0.0712
67	4.3	0.73	1.68	7.3	32.3	44.9	18.9	23.5	15.2	99	.0700
68	3.2	0.94	1.44	4.6	30.0	36.1	15.0	23.9	11.6	94	.0718
69	2.9	1.01	2.44	7.0	38.6	68.5	33.3	26.0	24.2	107	.0702
70	2.5	1.01	2.85	7.2	32.0	63.1	19.5	23.5	15.4	95	.0716
71	1.5	1.28	3.16	4.8	33.5	53.7	21.5	24.0	16.7	98	.0712
72	1.4	1.17	3.43	4.8	31.1	45.2	19.1	24.4	14.5	96	.0716
73	4.2	0.95	2.34	9.8	36.8	89.5	35.5	24.4	27.6	110	.0698
74	4.6	1.01	1.91	8.9	--	72.3	29.8	23.7	23.8	107	.0701
75	6.2	0.91	1.66	10.3	29.6	88.3	37.2	29.3	24.0	106	.0702
76	5.2	0.94	2.03	10.5	28.8	106.8	42.2	27.2	29.1	102	.0707
77	--	--	4.10	--	--	92.2	33.9	28.2	22.4	98	.0712
78	--	--	4.61	--	--	73.5	26.2	29.1	16.5	88	.0724
79	3.3	0.94	1.69	5.6	14.5	64.0	29.2	30.9	17.4	91	.0721
80	2.9	1.12	2.58	7.4	26.2	71.1	27.4	29.0	17.4	92	.0720
81	4.0	1.01	2.40	9.6	20.1	91.5	34.2	28.6	22.0	92	.0720
82	1.6	1.25	3.73	5.8	28.0	84.0	26.0	28.5	16.6	84	.0730
83	1.2	1.87	3.09	3.7	36.3	59.1	22.2	24.9	16.6	99	.0712
84	2.4	1.38	1.97	4.8	37.8	51.4	19.7	24.9	14.8	100	.0710
85	4.1	1.23	1.98	8.2	35.1	89.6	29.0	26.3	20.6	101	.0709
86	11.1	0.56	1.00	11.1	--	50.2	27.3	26.8	19.2	105	.0703
87	2.1	1.29	3.00	6.2	35.4	76.9	23.8	26.9	16.2	88	.0725
88	3.8	1.15	2.00	7.5	35.8	71.0	28.0	27.0	19.3	95	.0716
89	1.2	1.43	3.30	4.1	33.1	51.4	21.7	26.3	15.5	102	.0708
90	6.1	0.86	1.96	12.0	29.7	97.5	33.2	26.1	24.4	114	.0692
91	5.4	1.19	1.03	5.6	34.9	57.0	23.6	25.0	17.8	104	.0705
92	1.5	2.00	1.93	2.9	39.1	50.5	22.4	25.8	16.2	100	.0710
93	8.1	0.93	0.90	7.3	33.6	57.5	25.8	27.8	17.5	106	.0702
94	3.2	1.36	1.39	4.4	36.4	51.4	19.6	26.2	13.9	98	.0712
95	10.8	0.84	0.26	2.8	19.3	19.7	9.8	25.8	7.1	92	.0712
96	4.5	1.10	0.96	4.3	28.1	38.8	13.1	23.7	10.1	87	.0727
97	5.7	1.13	0.53	3.0	21.4	28.5	11.9	24.7	8.9	91	.0720
98	17.9	0.54	0.39	7.0	21.6	35.5	9.5	23.1	7.4	80	.0736

[1/] Stack area was 3.14 $ft.^2$

Table 6.--Experimental conditions[1/] and results for wind tunnel fires in cribs of white fir wood[2/]

Fire No.	Fuel and fuel bed parameters						Wind Speed	Flame[3/] variables		Burning parameters	
	ρ_f	W_f	h_b	w_b	L_b	S	$\bar{U}$	Φ	L	Q	R
	lb/ft^3	lbs	in	in	in	in	ft/sec	deg	in	Btu/sec	in/min
F 1	23.9	6.10	4.62	9.0	72.1	1.5	3.47	48.6	27.4	58.2	5.2
F 2	23.8	6.16	4.62	9.0	72.1	1.5	13.5	64.4	36.6	130.4	11.5
F 3	23.9	6.17	4.62	9.0	72.1	1.5	5.35	53.4	29.1	76.0	6.7
F 4	23.9	6.18	4.62	9.0	72.1	1.5	7.34	63.6	32.6	86.3	7.6
F 5	23.6	3.03	4.62	9.0	35.4	1.5	10.1	63.3	28.2	95.7	8.37
F 6	24.0	3.12	4.62	9.0	36.8	1.5	12.1	70.7	29.8	121.4	10.7
F 7	23.8	3.12	4.62	9.0	36.9	1.5	9.13	--	--	113.0	10.0
F 8	24.0	3.06	4.62	9.0	35.2	1.5	11.1	66.5	29.2	114.2	9.8
F 9	25.2	2.98	4.61	9.76	71.5	4.5	7.5	65.0	34.3	109.8	19.8
F10	22.6	2.67	4.63	9.76	71.5	4.5	3.74	56.1	23.3	60.5	12.2
F11	22.5	2.66	4.63	9.76	71.5	4.5	13.2	73.0	16.4	124.2	24.8
F12	22.8	3.76	4.63	8.5	71.8	2.5	7.43	63.2	24.4	79.0	11.2
F13	22.7	3.74	4.62	8.5	71.8	2.5	3.37	49.2	20.5	49.1	7.0
F14	25.2	4.16	4.63	8.5	71.8	2.5	13.1	72.7	15.3	31.8	16.8
F15	22.9	6.78	4.63	9.28	36.4	0.5	3.68	--	--	54.9	2.2
F16	22.6	6.70	4.62	9.28	36.4	0.5	7.41	58.8	22.1	63.2	2.56
F17	25.1	7.42	4.69	9.28	36.4	0.5	13.2	64.4	26.8	101.2	3.70
F18	25.1	3.20	4.62	9.0	35.3	1.5	9.6	--	--	99.3	8.16
F19	24.1	7.14	4.62	9.28	36.4	0.5	3.94	--	--	41.7	1.59

1/ Air temperatures were 71 $\pm$ 3°F.

2/ Stick thickness d_o = 0.252 inch and wood moisture content M_f = 10.3 $\pm$ 0.3 percent.

3/ Flame deflection angle Φ measured from vertical.

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